GAS BREAKDOWN IN THE SUB-NANOSECOND REGIME WITH VOLTAGES BELOW 15 KV

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Abstract

Gaseous breakdown in the sub-nanosecond regime is of interest for fast pulsed power switching, short pulse electromagnetics, and for plasma limiters to protect devices from high power microwave radiation. Previous investigations of sub-nanosecond breakdown were mainly limited to high-pressure gases or liquids, with applied voltages in excess of 100 kV. In this paper, we investigate possibilities to achieve sub-nanosecond breakdown at applied voltages below 7.5 kV in point-plane geometries. The setup consists of a pulser (risetime between 400 ps to1 ns), 50-Ω transmission line, axial needle-plane gap with outer coaxial conductor, and a 50-Ω load line. The needle consists of tungsten and has a radius of curvature below 0.5 μm. The constant system impedance of 50 Ω (except in the vicinity of the gap) and a special transmission-line-type current sensors enables current and voltage measurements with a dynamic range covering several orders of magnitude, with temporal resolution down to 80 ps. For pulse amplitudes of 1.7 kV (which are doubled at the open gap before breakdown) delay times between start of the pulse and start of a measurable current flow (amplitude > several milliamperes) have a minimum of about 8 ns, at a pressure of 50 torr in argon. Voltages of 7.5 kV produce breakdowns with a delay of about 1 ns. With negative pulses applied to the tip, at an amplitude of 7.5 kV, breakdown is always observed during the rising part of the pulse, with breakdown delay times below 800 ps, at pressures between 1 and 100 torr. At lower pressure, a longer delay time (8 ns at 50 mtorr) is observed. We expect the breakdown mechanism to be dominated by electron field emission, but still influenced by gaseous amplification.

I. INTRODUCTION

Gas breakdown in the subnanosecond regime is of vital interest for
- Plasma limiters [1], i.e. passive methods for the protection of electronic components using gas breakdown caused by the first cycle of incoming high power microwaves with frequencies in the GHz regime
- Ultra-wideband radiation sources, here gas breakdown during nanosecond pulses occurs mainly as corona discharges on wire antennas, and represents an unwanted effect
- General switching for pulsed power applications

Published data [2,3,4,5] for subnanosecond breakdown are mainly related to discharges in gases with pressures at or above one atmosphere, or for liquids, and for quasi-homogeneous electric fields which are at least on the order of several 100 kV/cm. For practical gaps, this means switching voltages for the subnanosecond regime of at least 100 kV.

For plasma limiters, where e.g. for S-band waveguides, power in the GW regime means electric fields of several 10^3 V/cm (or "voltage" across the waveguide on the order of 10 kV), breakdown in the subnanosecond regime for much smaller applied voltages is desirable. In this paper, we investigate breakdown in tip-plane geometries, where the field enhancement at either the cathode or the anode is sufficient to provide fast breakdown at applied voltage levels of less than 15 kV, for gas pressures between zero and one atmosphere.

II. EXPERIMENTAL SETUP

One of several sub-nanosecond risetime high voltage pulsers (1-1.7 kV with risetime of 0.5 ns using standard mercury relay switched pulsers, a Russian PNG-10 solid state pulser with an amplitude of 7.5 kV, and a high pressure switched pulser (Bournlea Instruments Ltd., Type 3148X, with an amplitude of 7 kV) is connected via a high voltage transmission line (two-way transit time 240 ns) and a high voltage vacuum feedthrough to a test gap in a vacuum, see Fig. 1. The other side of the test gap is terminated by another transmission line (load line) with a two-way transit time of 240 ns. A mesh outer conductor surrounds the test gap and the overall system has a constant impedance of 50 Ω, which enables fast electrical diagnostics. The pulser waveforms, measured with a current sensor integrated in a transmission line (see below) are depicted in Fig. 2.

Some measurements were done with a radial gap arrangement, in which the discharge connects the inner

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14. ABSTRACT
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with the outer conductor, and in which the pulser voltage is applied to the gap. Here, the pulse risetime (step response) is given by $\tau=ZC/2$. The majority of the measurements were performed with an axial gap, where the discharge connects the input transmission line via the inner conductors with the output transmission line. Here, the pulser voltage doubles at the open gap before breakdown, with a step response risetime of $\tau=2ZC$. For an impedance of $Z=50\ \Omega$ and an estimated capacitance, C, of several pF, both time constants are short compared to the pulse risetime.
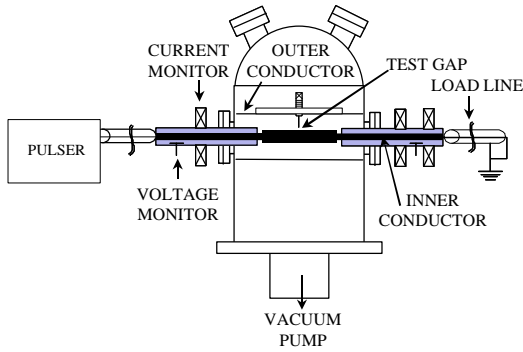

Figure 1. Experimental setup with radial discharge

The test gap consists of a tungsten needle (GGB Industries, Inc., Naples, Fl) with a radius of curvature measured with an electron microscope, at the tip of down to 0.2 µm, which has been operated at both polarities, and brass electrode with a radius of curvature of 5 mm at the other side. The maximum electric field is estimated[9] using $E_{max}/E_{av}=(h/r)+2$ to be about 500 MV/cm. At a pulser voltage of 7.5 kV, the needle tip is destroyed after one discharge, i.e. the tip is melted to a spherical shape with a radius of about 10µm. Main measurements were done in argon at pressures between several mTorr and 600 Torr.
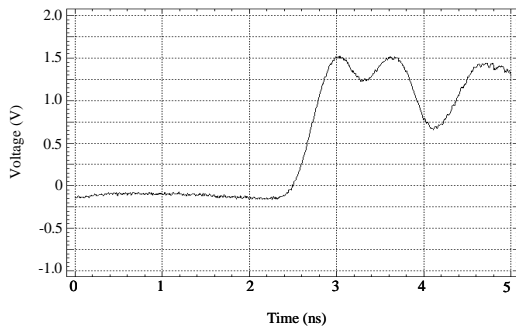

Figure 2 a) Output of Mercury relay pulser

The gap distance was 1 mm in all cases. Diagnostics include several transmission-line type current sensors [7] with a risetime below 400 ps and a sensitivity on the order of 1 V/A, and standard capacitive/resistive voltage dividers with a comparable risetime. It is planned to expand the current measurement setup to cover a dynamic range of six orders of magnitude using different current

sensors in combination with fast amplifiers and attenuators [8]. All signals were recorded with Tektronix
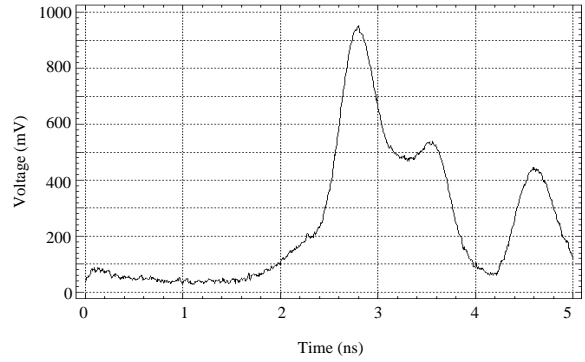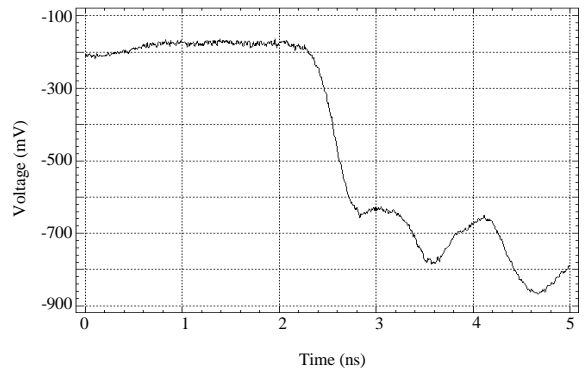

Figure 2 b) Output of PNG-10 pulser

Figure 2 c) Output of Bornlea pulser

SCD 5000 transient digitizers, with a sampling interval of 5 ps, and with an analog bandwidth of 4.5 GHz which corresponds to a risetime of 80 ps. All diagnostics cables used had an analog bandwidth of at least 8 GHz.

III. RESULTS

The majority of the measurements are based on the output of a current sensor located in the transmission line between pulser and gap, with a two-way transit time of 6 ns away from the gap. Predominantly, the axial gap arrangement has been used. Fig. 3 shows, as an example, a schematic picture of the expected waveform for an easier interpretation of the measured waveform, for an input pulse with a duration of less than twice the transit time between sensor and gap. Without breakdown, the current pulse is reflected with opposite polarity, arriving at the sensor after twice the transit time. A breakdown indicates gap closure, i.e. the current is transmitted through the gap again, and the reflected signal stops. Fig. 4 shows an actual measured pulse using the Bournlea pulser.

Fig. 5 shows breakdown delay times obtained with the mercury relay pulser, with positive tip and radial geometry, for a pulser voltage of 1.7 kV. Here, breakdown occurs after the pulse has reached its full

amplitude. Fig. 6 shows the delay times using the PNG-10 pulser, with positive tip, and axial geometry. Here,
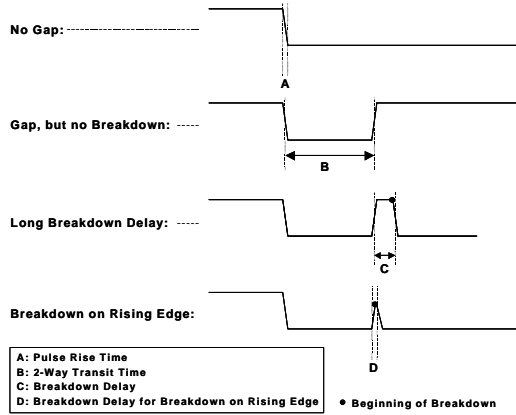

Figure 3. Schematic current waveforms for axial gap, with pulse duration larger than twice the transit time between sensor and gap
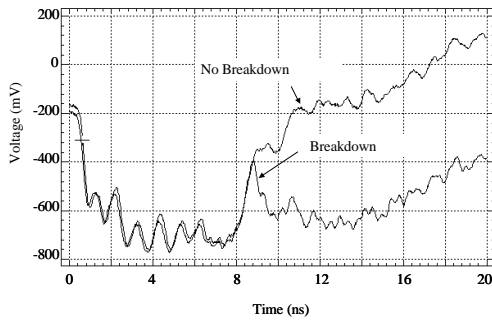

Figure 4. Measured waveform with Bournlea pulser, needle at negative polarity, axial discharge , 50 torr argon

breakdown occurs in approximately one nanosecond still during the rising part of the pulse, and might be even shorter if a shorter risetime pulse would be available.

Fig. 7 shows the breakdown delays for negative needle polarity, with axial gap, for the pressure range 0.5 to 600 torr, with an applied voltage of 15 kV.
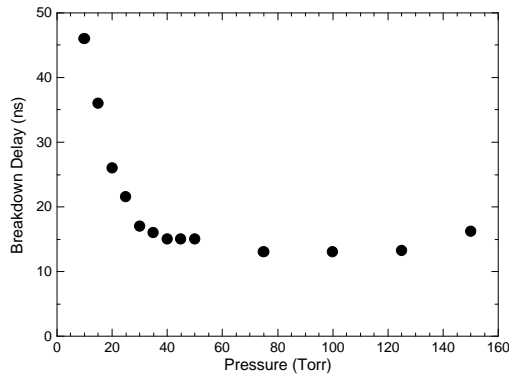

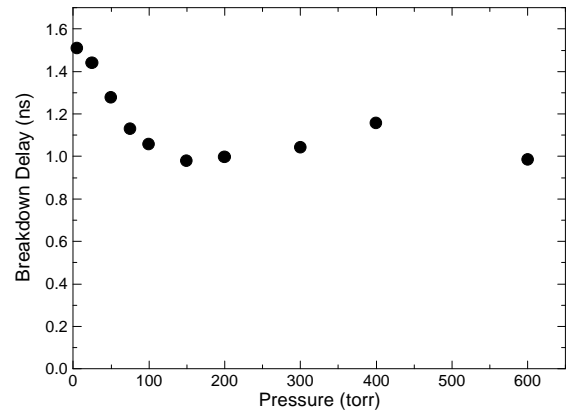**Figure 5.** Breakdown delay with pos. needle, radial geometry, at 1.7 kV in argon as function of pressure

Figure 6. Breakdown delay with pos. needle, radial geometry, at 14 kV in argon as function of pressure
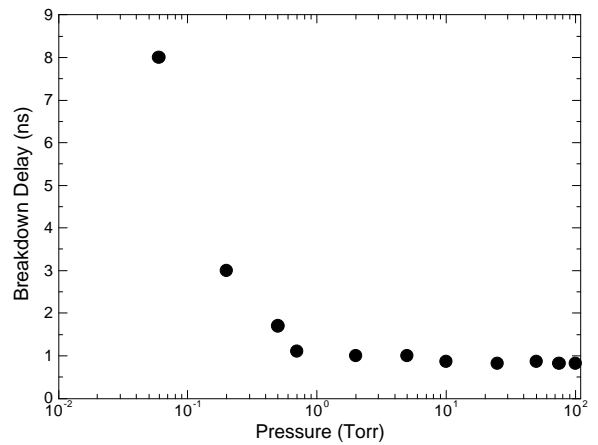

Figure 7. Breakdown delay with neg. needle, axial geometry, at 14 kV, in argon as function of pressure

IV. PLASMA LIMITER SIMULATION EXPERIMENTS

To test the actual working of plasma limiters based on discharges initiated by small radius of curvature tips, microwave breakdown experiments have been performed. The Texas Tech Traveling Wave Resonant Ring [9] was used, at a power level of close to 100 kW and the frequency 2.85 GHz. Two opposing needle holders and needles were mounted in a pressurable 20 cm section of the WR 284 waveguide used, with the needles parallel to the electric field in the fundamental mode, leaving a gap of 1 mm

Forward and reverse power in the ring, as well as signals from local electric field probes, are measured with standard methods [9], see Fig. 8 as an example. Peak power levels of the forward wave and breakdown delay times (time from the arrival of the incident wave at the gap to begin of the fall of the forward power in the ring) are depicted in Figure 9, as a function of pressure in argon.
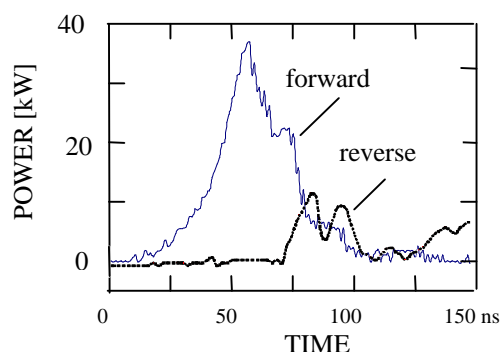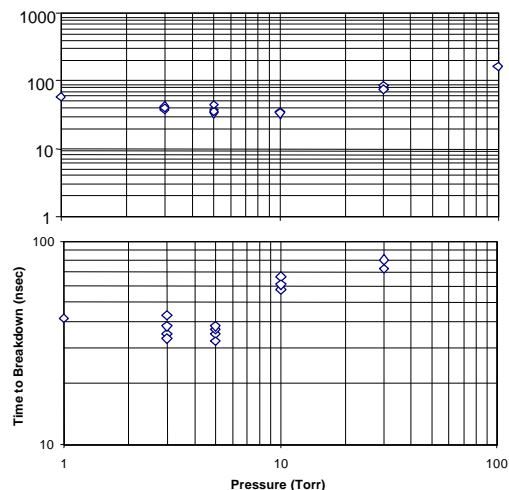
Figure 8. Forward and reverse power

Figure 9a) peak forward power
b) breakdown delay time as a function of
pressure in argon

V. DISCUSSION AND CONCLUSIONS

Breakdown delay times in the subnanosecond regime can be achieved with moderate voltages on the order of 10 kV in a tip plane geometry. With radii of curvature below 0.5 μm, breakdown delays are below one nanosecond for pressures larger than 1 torr in argon. The measured minimum values refer to breakdown during the pulse risetime, and thus represent an upper limit for the delay time.

The breakdown mechanism is far from being clear, and any attempt to model the observed type of discharge would have to treat the extremely inhomogeneous field geometry (macroscopic field enhancement of several 100 over distances of a fraction of a micrometer, i.e. shorter than the electron mean free path), and a time varying electric field, where the discharge development time is on the order of the time during which the field is applied. It is obvious that gaseous amplification and vacuum discharge mechanisms (such as electron field emission from negative tip) both play a role in the discharge mechanism.

The microwave experiments indicate that the proposed principle to construct a plasma limiter is viable. The double needle/gap arrangement has an almost negligible reflection coefficient without breakdown (indicated by zero reflected power in Fig. 8). At power levels of 30 to 150 kW (dependent on argon pressure) a plasma channel develops which reduces the forward power to zero within several 10 ns. This power level might be further adjustable by variation of the needle radius of curvature. In contrast to the dc experiments, where at applied voltage levels of 10 kV the needle tip is destroyed after one discharge, similar effects have not been observed for the microwave discharge. Therefore, it is expected that this plasma limiter principle can be extended to rep-rated operation, at least for power levels in the 100's of kW regime.

REFERENCES

1. A. Kikel, L. Altgilbers, I. Merritt, M. Brown, L. Ray, T.X. Zhang, Plasma limiters, American Institute of Aeronautics and Astronautics, paper AIAA-98-2564 (1998)]
2. T.H. Martin, An empirical formula for gas switch breakdown delay, Rs. Sci. Pulsed Power, Sandia Nat. Labs., pp. 73-79, (1991)
3. P. Felsenthal, J.M. Proud, Nanosecond pulse breakdown in gases, Phys. Rev. 139, pp. A1796-1804 (1965)
4. E. Kuhnhardt, Nanosecond pulsed breakdown of gases, in NATO ASI Series, Series B: Physics, vol. 89a, *Electrical Breakdown and Discharges in Gases*, Plenum Press, New York and London, 1983, pp. 241-263
5. J. Mankowski, J. Dickens, M. Kristiansen, High voltage subnanosecond breakdown, IEEE Transactions on Plasma Science 26, 874 (1998)
6. G.A. Mesyats, *Explosive Electron Emission*, URO Press, Ekaterinburg, 1998, pg. 24
7. H. Krompholz, K. Schoenbach, G. Schaefer, Transmission Line Current Sensor, IEEE Instrumentation and Measurement Technology Conference, Tampa, Florida, USA 1985, p. 224
8. A. Neuber, M. Butcher, L.L. Hatfield, H. Krompholz, Electric current in dc surface flashover in vacuum, J. Appl. Phys. **85** (1999) 3084
9. A. Neuber, D. Hemmert, H. Krompholz, L.L. Hatfield, M. Kristiansen, "Initiation of High power Microwave Dielectric Interface Breakdown ", J. Appl. Phys. **86** (1999) 172